Building specific catastrophe modeling for mid/high rise buildings supported by wind tunnel data

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ABSTRACT: Catastrophe modeling has been widely used to optimize portfolio management and facilitate public decision making for hazard mitigation. Among different natural perils, wind hazard imposed risk is one of the most significant. Three main aspects involved in catastrophe modeling includes hazard quantification, vulnerability assessment and monetary/economic impact prediction. Hazard quantification has been advanced in past decades due to advanced observational records, more powerful computational facilities and extensive research activities. Exposure data used for predicting monetary impact is also improved with more information collected. The estimation of building component failure includes significant uncertainties for mid/high rise buildings located in those coastal metropolitans, when generic models are applied. It is common for mid/high rise commercial buildings that geometry is unique and irregular and the surrounding building conditions are complex. Typically, wind tunnel tests are conducted to obtain accurate design pressures for cladding system and structural wind loads. Code calculated wind pressures are often used in modeling risk of building envelope breach when a generic model is considered. However, due to the complexity of the surrounding buildings and unique geometry of the building, code calculated pressures could introduce large uncertainties for specific buildings. The measured pressure distribution from the wind tunnel for specific building can be used to accurately quantify the risk of building envelope breach, which is one of the key failure modes for mid/high rise buildings. Structural failure is typically not being modeled for mid/high rise engineered buildings. However, there is still chances that the structural damage could occur at very high wind speed. The impact of considering the structural failure is investigated in this study. The developed vulnerability curve based on pressure calculated for generic model is compared to that developed by using building specific dataset.

Catastrophe modeling has become a popular tool for quantifying the natural hazard risk, advising mitigation planning, optimizing portfolio performance and facilitating public safety decision making. Three main aspects consist of typical catastrophe modeling, which include hazard assessment, risk analysis and financial/societal impact evaluation. Among these three key modules, the first two are critical. During the past decades, numerous efforts have been made to improve the outcome from the first two modules by shifting from empirical data fitting to scientific observation based numerical prediction and modeling, from claim data driven to engineering physics based modeling with adequate engineering adjustment inferred from claim data. Meteorological knowledge and numerical modeling have been intensively employed into the modeling process to quantify the long-term climate uncertainty and short-term variability. Hazard assessment and prediction only provide environmental actions, but not possible losses or injury due to catastrophic natural actions. Engineering module transfers the hazard to effects that cause different modes of failure, which typically includes non-structural failure, structure failure, victims and business interruption etc. Many research efforts have been focused on low rise buildings. However, value of mid/high rise buildings could take more than one third of the insured properties (Pinelli et al. 2010). These high value properties could have large impact on portfolio management, public safety and local economic performance. Engineering modeling for these high value properties could be challenging due to unique building geometry, complex surrounding and few accessibility of building information. Approach provided in building code might be used to quantify the design capacity and natural actions with some engineering adjustment (Pita et al. 2014). However, the load actions for mid/high rise building are typically much more complicated than what building code defines. Moreover, for mid/high rise buildings located in hurricane prone region, the design wind loads are typically consulted to wind engineering specialist by conducting wind tunnel study. In such a case, either the load actions or capacity defined based on code value would not be consistent with the real design. Therefore, towards precise catastrophe modeling for high value properties, it is necessary to employ the values used in the real design and load effects during the life time of the structure. For mid/high rise building catastrophe modeling, structural damage is seldom discussed. This is partly because entire structural failure has not been observed in hurricane wind event. However, the design philosophy indicates the probability of failure at design wind speed is not zero. The annual probability of exceedance of design wind speed is also not small enough to be entirely neglected. The impact of structural failure in the estimated loss ratio needs to be investigated. To accomplish this, the true design parameters need to be known.

This study employed wind tunnel database to develop building specific vulnerability curve. The effect of employing wind tunnel database on predicted loss ratio due to wind pressure and structural failure are specifically investigated.

1. BUILDING SPECIFIC ENGINEERING MODELING

One of the challenges for modeling high value properties is to precisely simulate the wind pressure field on building surface. High value properties are typically located in suburban and urban region, where the building surrounding for different wind coming directions is complicated. The building geometry is often unique. The complicated building surrounding indicates that the turbulent wind filed around the building is hard to predict by using simple empirical model nor analytical model. The accuracy of modeling wind pressure on building surface is critical for the estimated losses induced by building envelop breach.

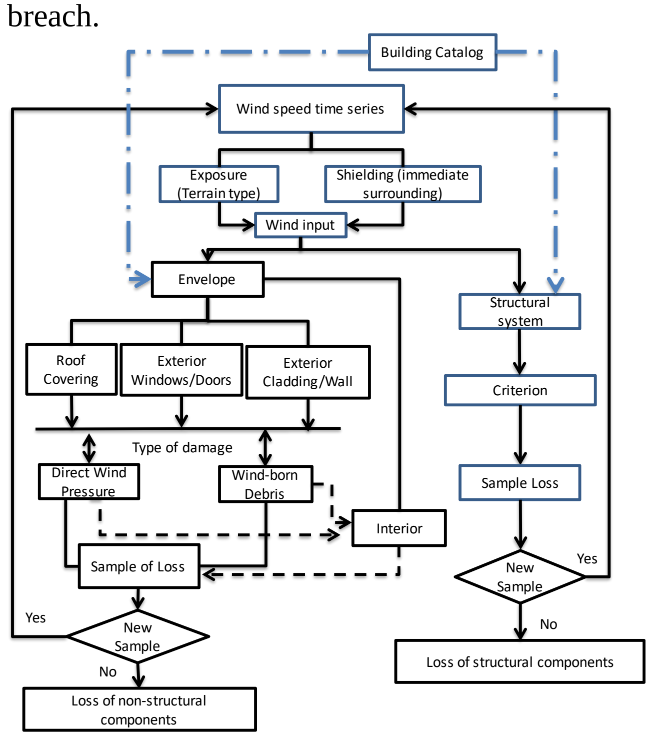

Figure 1: Flowchart of building specific catastrophic modeling.

It also needs to be stressed that for low rise buildings, generic model may provide sufficient accuracy for portfolio optimization and risk management, because each single low-rise building could not contribute significantly to the overall portfolio and nor creates large uncertainty to the overall risks. However, for mid/high rise building, its high property value could contribute a significant percentage of the overall exposures. Accurate prediction of the risk for high value property could be critical to reduce the uncertainty and provide better knowledge on risk management. A general framework for building specific catastrophe modeling is illustrated in Figure 1. Components of this framework are similar as that proposed in HAZUS (Vickery et al. 2006) and Florida Public Hurricane Loss Model (Pinelli et al. 2010). The hazard module is not explicitly defined in this framework, but will provide wind speed time series as basic input to this framework.

1.1 Wind pressure distribution measured from wind tunnel compared to code recommendation

Wind pressure is a fundamental variable for defining the actions on building cladding component or structural component. Wind pressure can be simply defined as a product of basic reference wind pressure and pressure coefficient. The reference wind speed is typically evaluated from the hazard module. Hurricane wind hazard modeling techniques (e.g., Li and Hong 2014 &2016) can be used to build up large database of hurricane induced wind speed time series for a specific location or region of interest for both short term or long-term period. Prediction of pressure coefficients highly depend on building geometry, surrounding environments, wind direction and its location. This indicates although two adjacent buildings would experience the same tropical cyclone wind, the pressure coefficients for a similar location could vary significantly. Most catastrophe modeling often use simple algorithm to estimate the pressure coefficients, especially for mid/high rise buildings. The first scheme extrapolates the pressure coefficients measured for low rise buildings to a certain height. The use of this algorithm is simply because public wind tunnel database is typically only available for low rise buildings. However, pressure field for mid/high rise buildings could be significantly different than that for low rise buildings. The second scheme is to use the code recommended pressure coefficient. However, since generic building models are used to derive code recommended design values, the real wind pressure for specific building could vary largely from code value.

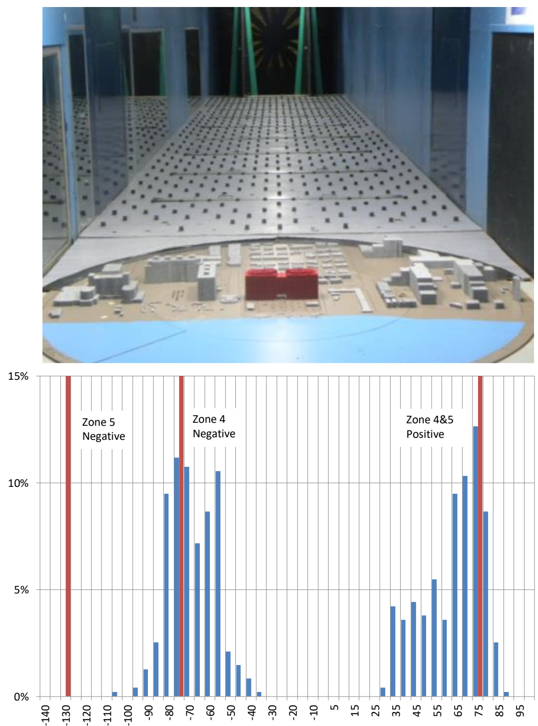

Figure 2: Example building geometry (top) and design wind pressure comparison (bottom).

An example is provided in Figure 2 to compare the code evaluated design pressure to those based on wind tunnel measurement for a high-rise building. Figure 2 also shows the design wind pressure estimated by ASCE 7-10. Four design values could be obtained from the building code for main walls that are positive and negative design pressure for central zone and positive and negative design pressure for corner zone. These values are illustrated by vertical straight lines in the plot. The evaluated extreme wind pressures at design wind speed for different locations obtained from wind tunnel test combined with the local wind climate are presented as histogram in the same plot. It can be observed that the evaluated extreme wind pressures based on wind tunnel measurement are different than that calculated based on building code. Design wind pressure evaluated from building codes is a specific percentile of the extreme value distribution of the peak wind pressure. Many building codes do not explicitly define this percentile (Ganvanski et al 2016). Even for those with a clear definition, it only indicates that a constant value is provided to the design team. However, for risk analysis, full probabilistic distribution of peak wind pressure is required. Building code does not provide the full probabilistic model for wind pressures. Some catastrophe models seem to use Normal distribution to describe the peak wind pressure with mean value defined as design wind pressure and standard deviation from some engineering judgement. Such approach could introduce large uncertainties for areas where negative suction is severe.

Studies (e.g. Cook and Mayne 1980, Li et al. 2017) have shown that extreme value distribution is appropriate for peak pressures for most cases. Although both design wind pressure and extreme wind pressure acting on a specific surface of the building could be estimated from the code approach, the distribution used to model the extreme wind pressures and resistance of building envelop components, e.g., cladding component, are different. Therefore, tail behavior of the true distribution cannot be simply well approximated by only considering matching the specific percentile value, i.e., design point. Accurate measurement of wind pressure distribution for specific building is important to improve the accuracy of the estimated losses due to building envelop breach.

1.2 Structural Failure

While ultimate limit state design is primarily concerned in structural design, catastrophe modeling for mid/high rise engineered buildings seldom considers structural failure. This is partly because the overall structural failure of mid/high rise building is rare. This is especially the case when well-engineered building is of concern. Although the rarity of the structural failure has no impact to the wind induced building losses at lower wind speed, it could have impact to the losses at higher wind speed, especially for extreme wind speed greater than design wind speed. For considering the structural failure, structural design wind load at ultimate design wind speed needs to be known. By incorporating the wind tunnel study, the wind load used in the final structural design is precise, which can be used to accurately define the characteristics of the structure capacity.

Full reliability analysis used in assessing structural failure needs to be consistent with the approach to define the ultimate limit state design in modern building code, e.g., ASCE 7-10, NBCC (2015). This study employs a framework similar as that presented in Ellinwood (1988) and Bartlett et al. (2003), but considers detailed design parameters. In this study, the overall base capacity of a structure is considered only, but not for each structural member. The structural failure is then defined as the event when the demand of the base loading induced by extreme wind events beyond the overall base capacity. The primary equilibrium between overall capacity and demand is set up such that,

$$\gamma R = \alpha_D D + \alpha_W W \tag{1}$$

where R, D and W are capacity, dead load effect and wind load effect, respectively. γ, α_D and α_W are resistance factor, dead load factor and wind load factor, respectively. For ASCE 7-10, α_W=1.0 with an ultimate return period of 700 years for Risk Category II building. In this study, the load effect considers base moment and shear, the capacity is assumed to be determined primarily by satisfying the above equilibrium. In other words, the wind load is dominant in all load combinations that governs the strength design. Such assumption is adequate for mid/high rise buildings that locate in tropical cyclone hazard prone region. The load effects for specific building are obtained by applying real design parameters that are used to determine the design wind load and used in the design. Moreover, as the wind load effect is determined by combining the wind tunnel test, the load effects for various wind speeds other than the design wind speed are obtained as well, which are used in developing the vulnerability curves against different wind speeds. The consideration of the structural failure has less impact in the estimation of the loss ratio at lower wind speed, but could have impact in the loss ratio at high wind speed that exceeds the design wind speed. An example of probability of failure derived from Eq. (1) is illustrated in Figure 3. The ratio is calculated by using the failure wind speed normalized by an ultimate design wind speed.

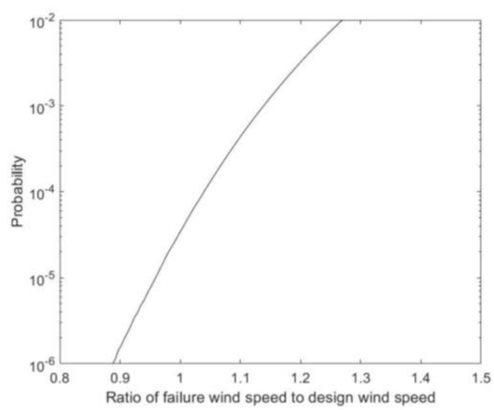

Figure 3. Distribution of probability of structural failure

For ultimate limit state design, a typical reliability index of 3.0 is defined by common category of safety requirement (ASCE 7-16, NBCC 2015). The corresponding probability of failure during the design life is about 1.35×10^{-3}. The annualized probability of failure provided in ASCE 7-16 for reliability index of 3.0 is about 3.0×10^{-5}. When the ratio in Figure 3 equal to 1.0, the probability of failure wind speed is roughly about the annual probability of failure. In this illustrating case, the probability is about 3.0×10^{-5}. As expected, Figure 3 shows that the failure wind speed is more likely higher than the ultimate design wind speed. Very large failure wind speed may not practical for developing vulnerability curves, as the corresponding return period of the associated losses could be too big to be considered in portfolio management. Figure 3 also shows that a moderate increase of the extreme wind speeds could increase the probability of failure considerably. Therefore, the effect of the structural failure around or above the ultimate design wind speed into the estimated loss ratio should be investigated.

2. BUILDING SPECIFIC VULNERABILITY ASSESSMENT

A catastrophe modeling framework could include hazard module, engineering module and financial/economic module. As the main purpose of this study focuses on improvement of the engineering module by incorporating wind tunnel measured pressure field in estimating the wind induced losses, other modules will not be comprehensively discussed. For predicting the extreme wind event induced building losses, wind hazard assessment can be estimated by using different techniques. For tropical cyclone prone regions, numerical simulation techniques are typically used to quantify the extreme wind hazard induced by tropical cyclones. Numerical simulation techniques (e.g. Vickery et al. 2009, Li and Hong 2014 & 2016) could be used for this purpose. The economic module estimates the values of building components, internal values of the building and replacement cost etc. could be setup as a generic model to consider the market mean value for a specific region, or building specific database when data is available. Since building specific exposure data is typically proprietary for high value properties, in this study, a generic economic module is used to emphasize the impact of incorporating a wind tunnel based engineering module in the estimated building losses.

2.1 Pressurization induced failure

Previous sections have shown the difference between the pressures evaluated from wind tunnel test compared to those estimated by using building code recommended values. This section takes an example building to show the effect of using wind tunnel estimated pressures in estimating the wind induced losses. The building has a square cross section as shown in Figure 2a. The terrain condition on one side is primarily suburban terrain roughness condition and the other side is open water terrain condition. The design wind pressures evaluated from wind tunnel test compared to those calculated by ASCE 7-10 building code is shown in Figure 2b. It can be observed from Figure 2b that the design wind pressure estimated by using ASCE 7-10 is conservative for the corner area compared to the value derived from the wind tunnel test, but less conservative for some of the central zone areas. This is because the spread of this building is wider than typical prototype square building used to derive pressure coefficient used in code recommendations.

The mean capacity of the glazing component of the building envelop is defined by the design wind pressures. The realization of the capacity for a specific glazing component is modeled as a random variable (Li et al. 2017), which meets the requirement defined by ASMS-E1300-07. The impact of selection of the probabilistic model in the estimated losses has been investigated in Li et al. (2017). In this study, the capacity of the glazing component is modeled as Weibull distribution. The probability of failure of an element is simply defined as the event when the wind pressure acting on a specific surface is greater than the realized capacity. The failure of each component is recorded for each wind event. The matrix of the failed component is setup for each simulated wind event. The loss of the building due to a specific wind event is defined as the total cost of replacement of the failed component or entire structure. In this section, several configurations are conducted as follows to investigate the effect of using wind tunnel measured true wind pressures.

- Configuration 1 (C1): Define both design wind pressure and demanding wind pressures by using wind tunnel evaluated values.
- Configuration 2 (C2): Define the design wind pressure using code values, but model the demanding wind pressures by using code values.
- Configuration 3 (C3): Define both design wind pressure and demanding wind pressures by using code values.

The first configuration is used as a benchmark in this study, as both design values and demanding pressures for the tested specific building is known from measurement. The second configuration is designed to show the effect of using code value to define the capacity. The third configuration is often the case when both true design value and demanding pressures are not available to the modeling team. Therefore, code based estimate is adopted. The demanding wind pressures defined by using the code value are modeled as a Normal distribution with the mean value equal to the code calculated design wind pressures and the coefficient of variation of the extreme pressures is set to be 0.1. The parent distribution of the demanding wind pressures is directly evaluated from the wind tunnel measurement. The realization of the demanding wind pressures is randomly simulated from these evaluated parent distributions. The loss ratio is defined as the ground up cost to replace the damage components of the building. In this study, as the internal losses are not considered, the loss ratio is the cost of replacement to the total cost of re-build the building. A value of 30% of the total cost of the envelop of the building is assumed in this case study.

It can be observed in Figure 4 that C2 estimates higher loss ratios. This is because the capacity defined for the central zone by using the code evaluated values are generally lower than that measured from wind tunnel study in this case. Although the capacity of the corner area defined by using the code recommended value is conservative and higher than that evaluated from wind tunnel study, the overall area of corner area in this study is less than the central area. At lower wind speed, the estimated loss ratio from C1 and C2 are very close. The difference between C1 and C2 becomes apparent from sustain wind speed of 100 mph. The maximum difference of the estimated loss external loss ratio could be more than 5% for this case study. While the different seems to be not large, it should be notice that the case study building is in a not complicated surrounding environment with general standard geometry.

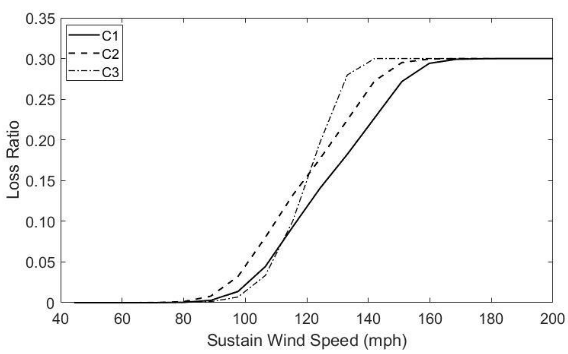

Figure 4. Vulnerability curves for different configurations

Although the building code could generally provide a good estimate of the design wind pressures, as the main central zone in this building facing towards open/suburban terrain and has a wider spread than usual square building, the actual design value would be higher than the code predicted values. Possible uncertainties of the estimated design value compared to code recommended values are not rare for mid/high rise buildings with unique geometry and not standard terrain surroundings.

For C3 where both capacity and extreme wind pressures are modeled by using the values evaluated from building code, the estimated loss ratio could be overestimated in this specific case study. The uncertainty of the estimated loss ratio by using code value for both capacity and demand highly depends on the probabilistic model adopted. As the code does not provide any characteristic values of the extreme wind pressure/pressure coefficients, the adequacy of the assumed distribution parameters could be critical.

2.2 Impact of structural failure

This section takes C1 as an example, but considering structural failure. The failure event in this case consists of pressure induced building envelope failure and structural failure. The structural failure induced losses is simply considered as 100%. The structural failure could also occur at speed lower than the design wind speed as indicated in Figure 3. The developed vulnerability curve is presented in Figure 5. For comparison purpose, the curve developed for C1 is also presented. It can be observed that the difference between these two curves at lower wind speed is very small (only about ~2%). However, the difference between these two curves for wind speeds greater than about 160 mph becomes apparent. At extremely high wind speed, the loss ratio considering structural failure could be more than 20% more than that only considering building envelope non-structural failure.

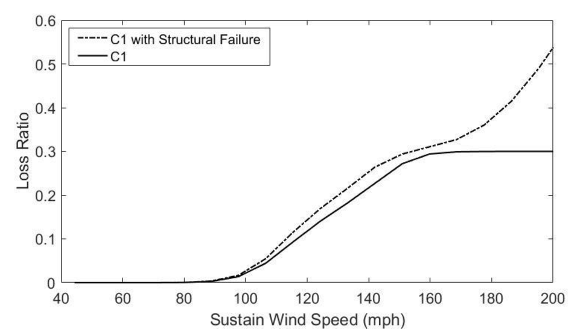

Figure 5. Developed vulnerability curve considering structural failure

Although such difference occurs only at very high wind speed, such low probability but high severity risk is critical for portfolio management for the property owner, insurance and re-insurance company and valuable for public decision making. The impact of considering the structural failure in the estimated losses for high value properties could vary largely. This is because the characteristics of the design parameters are different. When wind interference induced wind loads are dominant, the critical wind speed could be lower than the design wind speed. In this scenario, the impact of considering the structural failure into the developed vulnerability curve will shift to the lower wind speed part, which deserves more concern in risk and portfolio management.

3. DISCUSSION AND CONCLUSIONS

A framework of building specific catastrophe modeling is introduced in this study. The general components of this framework are similar as those used in catastrophe modeling industrial and public funded hurricane loss model. The input and process of the engineering modules are improved by incorporating the design parameters and measured pressure field from building specific wind tunnel test. The design value for building envelop and structural design wind load are derived from wind tunnel test and used in the real design. These precise values reduce the uncertainty of the estimated losses for specific high value property compared to those estimated by using generic vulnerability curves. The effect of using building specific design value into the estimated losses compared to those estimated by using code estimates is presented. Uncertainties of the developed vulnerability curve can be reduced by incorporating the design parameters. Although structural failure is rare for well-engineered high value property, the consequence for such failure is devastating and cause significant financial loss. Structural failure could be important for the developed vulnerability curve at very high wind speed. For cases that critical wind speed is dominated by interference wind effect and is lower than design wind speed, loss ratio at lower wind speed will increase.

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